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REVIEW ARTICLE

Space Debris Mitigation Activities of Indian Space Research Organisation: Ongoing Efforts and Future Roadmap

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Abstract
As a responsible space-faring agency, Indian Space Research Organisation (ISRO) places high importance on space debris mitigation. Currently, ISRO follows and strives to improve compliance with the relevant internationally accepted guidelines, which involves incorporating appropriate measures during the design, operation, and disposal phases. In this paper, we present space debris mitigation efforts undertaken by ISRO. The measures include limiting the release of mission-related objects, preventing on-orbit accidental explosions through robust design measures and end-of-life 'passivation' or removal of active energy sources, operational collision avoidance for launch vehicles and spacecraft, disposal of satellites and launch vehicle upper stages at their end-of-life away from densely populated regions so that they do not pose any collision risks to other operational space objects. We focus on specific efforts undertaken to improve compliance with the mitigation guidelines. The challenges faced and the lessons learnt, inputs to space policy directives to promote space sustainability are also highlighted. We then present various activities undertaken to raise awareness of the growing space environmental concerns and ways to address them. We conclude with the future roadmap, which includes the Debris Free Space Mission, a major endeavour on space sustainability spearheaded by ISRO.

Keywords Space debris mitigation · Post-mission disposal · Space Object Proximity Analysis · Collision avoidance analysis · Debris Free Space Mission

Introduction

In recent years, the space environment has been drastically transformed by the rapid increase in the number of objects launched into space, contributed by the phenomenal advances in space technology and the ever-widening scope of space applications. As of now, most of the objects in outer space are space debris, which are human-made objects in space that serve no useful purpose. They consist of non-functional spacecraft, rocket bodies, their fragmented parts, and objects released during on-orbit operations (Klinkrad 2006). One major source of space debris is accidental breakup or fragmentation of satellites and rocket bodies (Anz-Meador et al. 2023). Historically, the numerous intentional self-destructs of satellites and a few Anti Satellite Tests (ASAT) have resulted in a large number of fragments. On-orbit collisions, though relatively rare, also contribute to the space debris population. Another issue is that the debris generated due to fragmentation (accidental or intentional break-up, or collision) eventually spreads across all inclination regions. Only those in the lower altitude orbits are short-lived as they re-enter the atmosphere, the rest continue to orbit the Earth posing collision threats. Furthermore, with the proliferation of large constellations leading to spikes in space object population in certain orbital regions, ensuring safe and sustainable operations in outer space has become a major challenge, both for current and future operators (Anil Kumar 2024a). With the growing dependence on space for critical uses such as communication, navigation, Earth observation, and scientific research, it becomes imperative to adopt practices that minimize negative impacts and maximize the long-term benefits of space activities.

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There has been a unanimous agreement at an international level that space-based activities must be properly managed and supervised to contain the space debris population growth. Space Debris Mitigation includes measures for reducing the generation of new orbital debris and ensuring the operational safety of space assets. Recognising the growing concern after an accidental break-up of an Ariane rocket body in 1992 that created hundreds of debris, the Inter-Agency Space Debris Coordination Committee (IADC) (IADC 2024) was formed in 1993 as an international organisation to address all issues related to space debris. The main aim was to exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperation activities and to identify and evaluate debris mitigation options. The foundational guidelines for space debris mitigation were formulated by IADC in 2002, which have undergone a few revisions (IADC Working Group 2021). To this date, IADC is the most recognised international body dealing with technical studies related to space debris.

IADC defined two special zones which are unique in nature, namely, Geosynchronous (GEO) and Low Earth Orbit (LEO), as protected regions (IADC Steering Group 2021; IADC Working Group 2021), as shown in Fig. 1. These regions are highly utilised and any debris creation within them would have detrimental effects on the long-term sustainability of outer space activities.

The IADC guideline formed the baseline for a set of guidelines for space debris mitigation by the United Nations Committee on the Peaceful Uses of Outer Space (UN-COPUOS). Formulated to be higher-level and qualitative for a wider acceptance among the global space-faring nations, and in consideration of the United Nations treaties and principles on outer space, the UN-COPUOS guidelines were adopted by the Scientific and Technical Subcommittee (STSC) of the UN in 2007. On 22 Dec 2007, the UN General Assembly endorsed the guidelines and encouraged all member states to adhere to them voluntarily. The core principles of the guidelines for space debris mitigation recommended by IADC and UN-COPUOS are limiting debris release during normal operations, post-mission disposal of space assets, avoiding on-orbit collision, and minimising the potential for on-orbit break-ups. These guidelines form a basic framework for the non-proliferation of debris and are translated into standard engineering practices by spacefaring nations in line with their respective national policies. As a responsible space agency, ISRO follows UN-COPUOS/IADC space debris mitigation guidelines (SDMG) to the maximum extent possible and practicable (Anil Kumar 2022, 2024b). The debris mitigation measures adopted include passivation of upper stages, launch collision avoidance (COLA) assessments, close approach analyses for operational satellites, post-mission disposal of GEO satellites to super-synchronous graveyard orbits, and end-of-life de-orbiting of LEO satellites and rocket stages to minimize their post-mission presence in LEO.

In this paper, we present ISRO's ongoing efforts to comply with the SDMG and a future roadmap under the broader scope of ensuring the long-term sustainability of outer space

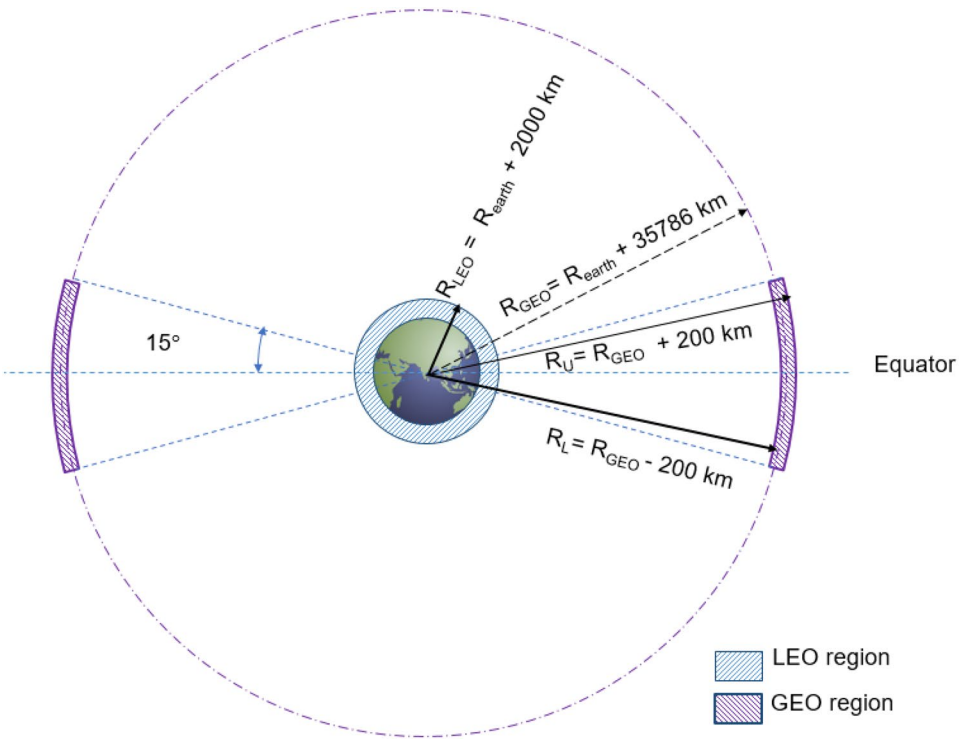

Fig. 1 IADC defined GEO and LEO protected regions. R_{earth}= Earth's radius, R_{LEO} defines the upper limit of LEO region; R_L and R_U lower and upper limits of the GEO protected zone

activities. The paper is organised as follows. We start with an overview of the internationally accepted SDMGs followed by the implementation details. We present the conjunction analysis methodologies for launch vehicles and satellites, passivation, and post-mission disposal of orbital stages and satellites with specific examples. Environmental modelling aspects which have a direct bearing on space asset protection and the estimation of ground casualty risk posed by uncontrolled re-entries are also presented. We discuss the challenges faced and lessons learnt and conclude with the future roadmap.

Space Debris Mitigation Guidelines

To start with, we summarise the key principles of the IADC and UN-COPUOS guidelines below:

1. *Limit debris released during normal operations:* Space systems should be designed not to release debris during normal operations. If this is not feasible, the effect of any release of debris on the outer space environment should be minimized.
2. *Minimize the potential for break-ups during operational phases:* Spacecraft and launch vehicle orbital stages should be designed to avoid failure modes which may lead to accidental break-ups. In cases where a condition leading to such a failure is detected, disposal and passivation measures should be planned and executed to avoid break-ups.
3. *Limit the probability of accidental collision in orbit:* In developing the design and mission profile of spacecraft and launch vehicle stages, the probability of accidental collision with known objects during the system's launch phase and orbital lifetime should be estimated and limited. If available orbital data indicate a potential collision, adjustment of the launch time or an on-orbit avoidance manoeuvre should be considered.
4. *Avoid intentional destruction and other harmful activities* Recognizing that an increased risk of collision could pose a threat to space operations, the intentional destruction of any on-orbit spacecraft and launch vehicle orbital stages or other harmful activities that generate long-lived debris should be avoided. When intentional break-ups are necessary, they should be conducted at sufficiently low altitudes to limit the orbital lifetime of resulting fragments.
5. *Minimize the potential for post-mission break-ups resulting from stored energy* To limit the risk to other spacecraft and launch vehicle orbital stages from accidental break-ups, all onboard sources of stored energy should be depleted or made safe when they are no longer required for mission operations or post-mission disposal (PMD).
6. *Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission* Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the LEO region should be removed from orbit in a controlled fashion. If this is not possible, they should be disposed of in orbits that avoid their long-term presence in the LEO region.
7. *Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit (GEO) region after the end of their mission* Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the GEO region should be left in orbits that avoid their long-term interference with the GEO region.

Over the years, ISRO has developed substantial capabilities for space debris-related analyses and made significant contributions to protecting operational Indian assets (Anil Kumar 2022). A historical perspective of ISRO and India on the growing problem of space debris is presented by Prasad (2005). The establishment of the ISRO System for Safe and Sustainable Space Operations Management (IS^4OM) marks another major milestone (Indian Space 2024a). In addition to all activities related to space debris mitigation, its scope of activities includes the establishment of dedicated observational facilities (RADARs, optical telescopes) to obtain more accurate orbital information of space objects, coordination with national and international bodies to avoid on-orbit collisions, collaboration with academia and research institutes for the assessment of the orbital space debris environment, engagement with emerging Indian space sectors to raise the awareness on the importance of space debris mitigation for the long-term sustainability of space activities. We further elaborate on the mitigation-related activities in the next sections.

Collision Avoidance

In this section, we discuss the prevalent methodologies to safeguard space assets, namely satellites and launch vehicles, against any on-orbit accidental collision risks.

Collision Avoidance Analysis (COLA) for Launch Vehicles

Pre-launch conjunction assessment is carried out to identify potential collision threats from space objects during

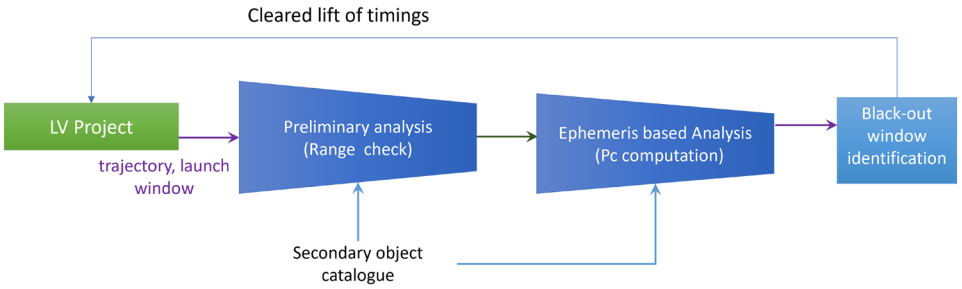

Fig. 2 Top-level workflow and interfaces of LV-COLA

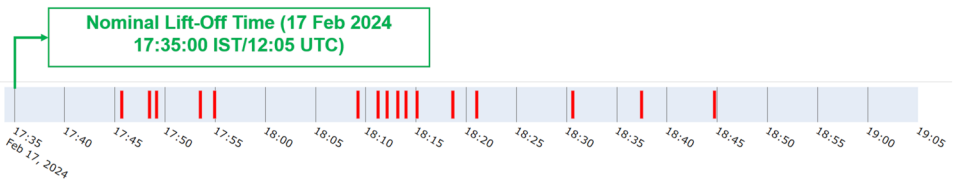

Fig. 3 Blackout zones within launch window for GSLV-F14 mission are shown by red bars

the ascent phase of launch vehicles (LV) and the initial orbital phase of the injected satellites. It is a part of the mandatory Launch Clearance Protocol of all ISRO launch vehicles, namely Polar Satellite Launch Vehicle (PSLV), Launch Vehicle Mark-3 (LVM3), Geosynchronous Satellite Launch Vehicle (GSLV), and Small Satellite Launch Vehicle (SSLV). Basic inputs are the orbital elements of space objects from USSPACECOM, operator-shared ephemerides (wherever available), nominal injection parameters of the injected S/C, LV trajectory, and the launch window. COLA is performed to identify the safe lift-off timings within the entire launch window. In ISRO, the analysis is initiated about a week before the launch and repeated every day with the updated LV trajectories. The time instances within the launch window where a lift-off would result in critically close approaches to other space objects are marked as blackout zones. For a given lift-off time, a conjunction is flagged as critical if a pre-defined threshold on the probability of collision is exceeded. The corresponding lift-off timing is not recommended within these time zones. The overall scheme is shown in Fig. 2.

An additional time window (usually ±10 sec, which corresponds to the worst-case dispersion in the injection timing, as obtained through Monte-Carlo analyses) centred around a given blocked lift-off epoch is also forbidden for lift-off, such blackout windows are shown in Fig. 3

The analysis specifically addresses any close approach with the crewed missions like the International Space Station (ISS) and Tiangong/Chinese Space Station (CSS) with a wider close approach distance screening threshold. Any close approach with an active satellite is notified to the concerned Owner/Operator with a request to avoid manoeuvring their satellite till the end of the predicted close approaches. The necessary coordination is also carried out to acquire more accurate operator-provided ephemerides for improving the accuracy of collision risk assessment.

Table 1 lists the occasions when the lift-off for ISRO launch vehicles was delayed. Figure 4 depicts a typical case of PSLV-C58 where delaying lift off mitigated the conjunction risk.

Conjunction Assessment for Satellites

Space Object Proximity Analysis (SOPA) process has been in place for nearly two decades to assess any potential collision risks between ISRO's satellites (primary objects) and other resident space objects (secondary objects) (Bandyopadhyay et al. 2004). SOPA has evolved over the years to incorporate the newer requirements arising out of a rapidly transforming space. The process involves predicting the expected positions of the primary and other space objects over a certain time interval into the future. Any other object (secondary object) within a spatial volume centred at the space asset (primary object) indicates a possible conjunction warranting further assessment of actual conjunction risk.

There is an inherent uncertainty associated with a space object's instantaneous positional knowledge, usually quantified in terms of a covariance. Such uncertainties must be addressed under a suitable probabilistic framework while estimating collision risk. The probability of collision (P_c) is the most widely used metric for collision risk management. It is defined as the likelihood that the miss distance between the two bodies under conjunction is less than their combined sizes, represented as the hard body radius. Hard-body radius (HBR) is defined as the radius of the circumscribing sphere of a space object; formulation in terms of HBR helps eliminate the need for attitude motion consideration. The encounters between objects are usually short, which allows approximating the relative motion as a rectilinear one and further simplifications. P_c can be found by evaluating the 2-D integral of the joint probability density function, which

Table 1 List of launches where lift-off was modified by COLA recommendation

Mission	Nominal liftoff time (IST)	Delayed by	Actual liftoff time (IST)
PSLV-C18/Megatropiques-1	12 Oct 2011, 11:00:00	1 min	12 Oct 2011, 11:01:00
PSLV-C21/SPOT-6	06 Sep 2012, 09.00:00	2 min	06 Sep 2012, 09.02:00
PSLV-C20/SARAL	25 Feb 2013, 18:00:00	5 min	25 Feb 2013, 18:05:00
PSLV-C23/SPOT-7	30 Jun 2014, 09:49:00	3 min	30 Jun 2014, 09:52:00
PSLV-C32/IRNSS-1F	10 Mar 2016, 16:00:00	1 min	10 Mar 2016, 16:01:00
PSLV-C36/Resourcesat-2A	07 Dec 2016, 10:24:00	1 min	07 Dec 2016, 10:25:00
PSLV-C39/IRNSS-1 H	31 Aug 2017, 18:59:00	1 min	31 Aug 2017, 19:00:00
PSLV-C40/Cartosat-2F	12 Jan 2018, 09:28:00	1 min	12 Jan 2018, 09:29:00
PSLV-C42/Novasar S1-4	16 Sep 2018, 22:07:00	1 min	16 Sep 2018, 22:08:00
PSLV-C43/Hysis	29 Nov 2018, 09:47:00	30 s	29 Nov 2018, 09:47:30
PSLV-C53/DS-EO	30 Jun 2022, 18:00:00	2 min	30 Jun 2022, 18:02:00
PSLV-C55/ TeLEOS-2	22 Apr 2023, 14:19:00	1 min	22 Apr 2023, 14:20:00
LVM3-M4/Chandrayaan-3	14 Jul 2023, 14:35:13	4 s	14 Jul 2023, 14:35:17
PSLV-C56/DS-SAR	30 Jul 2023, 06:30:00	1 min	30 Jul 2023, 06:31:00
PSLV-C60/SPADEX	30 Dec 2024, 21:58:00	2 min 15 s	30 Dec 2024, 22:00:15

models the positional uncertainties, usually as a bivariate Gaussian distribution, over the combined HBR circle at the encounter plane perpendicular to the relative velocity vector.

An estimate of the maximum probability of collision (P_{cmax}) is used in SOPA for collision avoidance decision making.

In its early days, SOPA was performed once daily and was limited to deriving and using the orbital information of the threat bodies from the publicly available two-line element (TLE) data. The orbits of all the primary satellites were propagated from initial state vectors. As a result, any orbit manoeuvre was treated as an impulsive manoeuvre and screened in parts as pre-manoeuvre and post-manoeuvre trajectory as a reasonable assumption for short-duration burns. The present conjunction analysis process supports all the legacy formats and has been upgraded to include orbital information in various other formats and coordinate frames for both primary and secondary objects. Conjunction assessment screening is typically done over a 7-day duration using TLE data sourced from USSPACECOM (United States Space Command) (Space Defense 2024) and for the ephemeris availability duration of the secondary objects. The usage of orbital ephemeris allows seamless screening of satellite trajectories even in the presence of multiple manoeuvres within a trajectory. It also adds the capability to screen finite burn manoeuvres without any need to simulate the burn.

In practice, the alarm thresholds are set according to the orbital regime (LEO, GEO) and periodically tuned based on operational experience and evolving space environment. Additional safety margins are imposed for inhabited assets through more conservative thresholds. In case a close approach is detected that might result in a collision risk, necessary actions are initiated. The top-level interfaces for SOPA are shown in Fig. 5. A typical timeline for CAM decision-making and authorising its execution is shown in Fig. 6.

If the threat object is a piece of debris or a non-manoeuvrable defunct object, the most straightforward action is to perform a propulsive manoeuvre to change the orbit of the primary satellite. However, such collision avoidance manoeuvres (CAM) need careful consideration before execution. Every manoeuvre consumes on-board fuel and fuel usage results in a reduction of the satellite's operational life, loss of payload tasking opportunities, and sometimes also needs additional fuel to perform a restitution manoeuvre to return to the nominal mission orbit. Therefore, in case of a conjunction, whenever possible, collision avoidance manoeuvres are designed to be favourable for orbit maintenance.

CAM design, like any other manoeuvre design, is dictated by both onboard and ground constraints. The goal is to reduce the probability of collision at the time of closest approach. The main parameters of a CAM plan are the magnitude, direction, and time of burn to realize the desired velocity change. Each CAM plan goes through a SOPA screening with its post-manoeuvrer expected orbit to

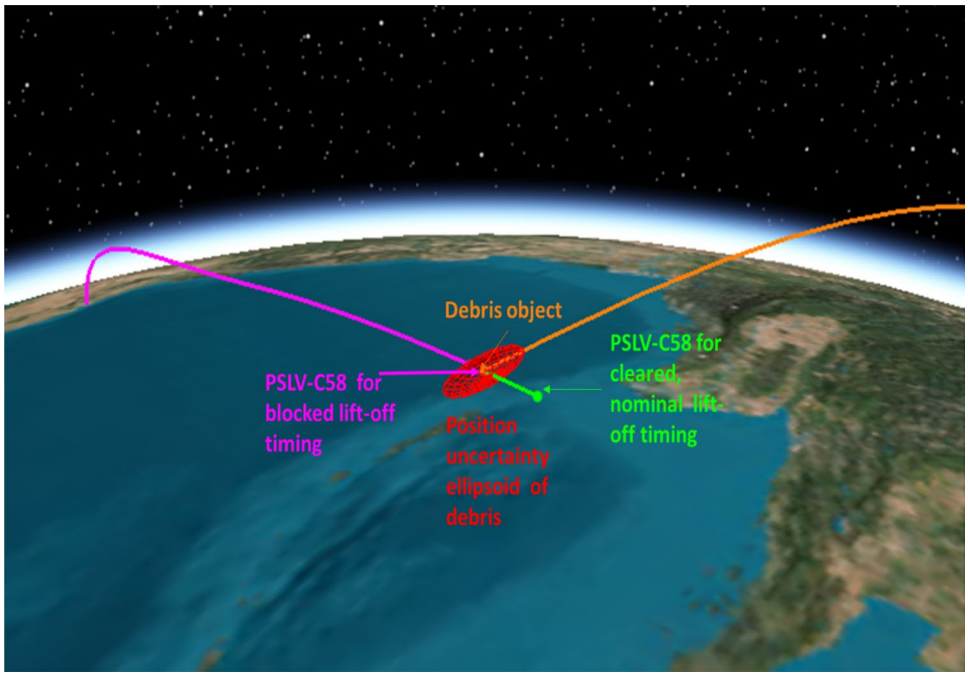
Debris object
PSLV-C58 for blocked lift-off timing
PSLV-C58 for cleared, nominal lift-off timing
Position uncertainty ellipsoid of debris

Fig. 4 Depiction of on-orbit conjunction between launch vehicle trajectory and a space object for cleared and blocked lift-off timings

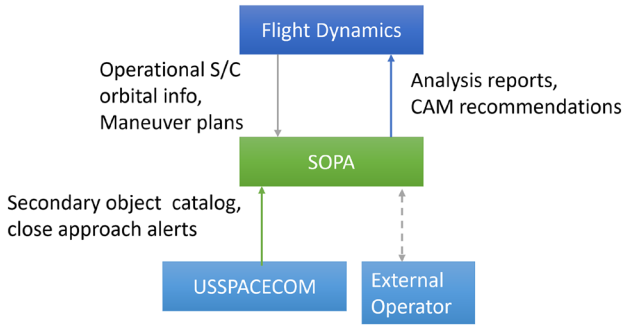

Fig. 5 Top level SOPA interfaces

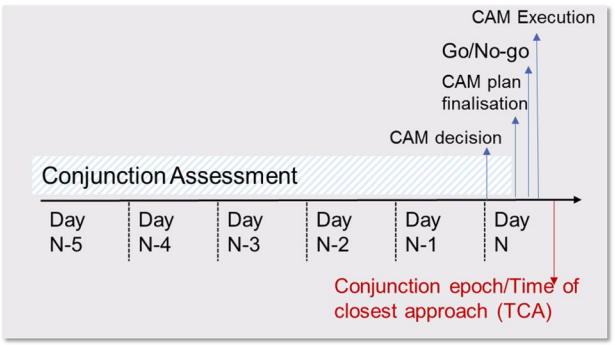

Fig. 6 Timeline of CAM execution

ensure that the CAM execution does not give rise to fresh conjunctions.

Figure 7 illustrates how the miss distance of a particular conjunction is improved as the result of a CAM.

In case of conjunctions between two active satellites, the owner/operators of both the satellites normally exchange ephemerides. Conjunction analysis with operator ephemeris gives the most accurate conjunction assessment. If the operator ephemeris-based conjunction assessment indicates the necessity of an avoidance manoeuvre, only one of the satellites is manoeuvred based on the mutual consent of the satellite operators. It is also a regular practice for the other operator to keep a backup plan ready in case the planned CAM cannot be performed due to unforeseen circumstances. The conjunction assessment process screens the orbits of all ISRO satellites against the obits of all other resident space objects. Currently, the process relies on the Space-Track database and the available operator ephemerides for the screening of conjunctions. The results of screening are provided to all the stakeholders along with recommendations for collision avoidance manoeuvre as and when required. Figure 8 shows the collision avoidance manoeuvres executed by Earth-orbiting ISRO spacecraft from 2010 to 2024.

Since 2020, ISRO has evolved a methodology for conjunction assessment of its Mars and Moon orbiting spacecraft, namely BEARCAT (Beyond Earth oRbit Conjunction AssessmenT). Now, the special characteristics of deep-space missions are as follows:

- The position accuracy can be poorer compared to Earth-bound missions, mainly due to the vast distance and the uncertainty in the modelling of the dynamics involved.
- The uncertainty in defunct satellites' orbit is very large because, unlike orbital debris, they are not tracked. Hence, most of them are often considered "lost".

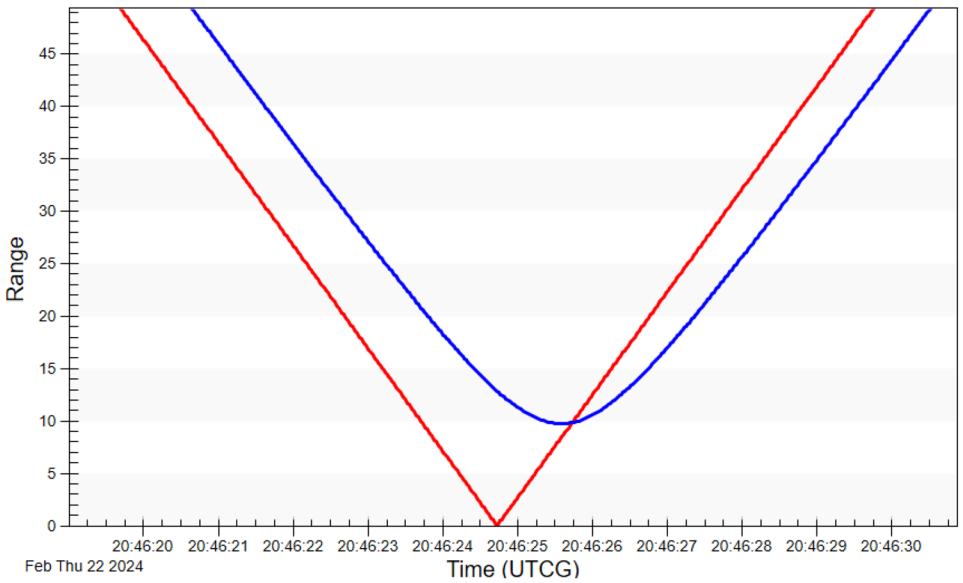

Fig. 7 A typical case of mitigation of collision risk through a CAM (red curve shows the miss distance variation before CAM and the blue curve corresponds to the post-CAM situation)

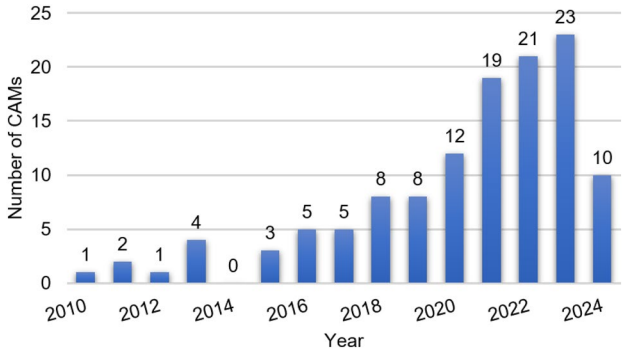

Fig. 8 CAM statistics for ISRO's LEO and GEO satellites (2010–2024)

- The update in ephemeris is relatively infrequent, of the order of days or weeks compared to the update frequency of hours/days for Earth-bound satellites.
- The 'small-force' due to momentum unloading by firing thrusters non-negligibly impacts the long-term evolution of the orbit.

As a result, deep-space conjunction assessments are limited to active secondary objects and CAM decisions have a higher lead time, typically a couple of days. During this lead time, additional measurements can be obtained to have a better estimate of satellite orbit and re-assess the situation. International cooperation plays a crucial role because the latest and most accurate operator ephemerides, inclusive of any planned manoeuvre effects, need to be shared for more accurate assessment (Mukherjee and Anil Kumar 2023). In general, using a common source of ephemerides is necessary to arrive at a common operational picture for different space agencies involved. This consideration is especially important for deep-space missions as any collision avoidance strategy must be devised based on mutual understanding and consent.

BEARCAT is currently operational for Chandrayaan-2 Orbiter/CH_2O and Aditya-L1 missions, it was used for Mars Orbiter Mission and Chandrayaan-3 mission during their active orbital phase around Mars and the Moon, respectively. All manoeuvre plans for CH_2O are screened by BEARCAT to avoid any post-manoeuvre potential conjunction with other neighbouring orbiters. On several occasions the manoeuvrer plans have been "tweaked" or the burn timings/manoeuvrer dates are shifted based on spaceflight safety considerations. As the analysis duration spans almost a month, in most the cases any potential conjunction risks are mitigated by modifying the immediately next scheduled orbit manoeuvre plan. Till November 2024, four CAMs have been performed for CH_2O, the first one being on 18 Oct 2021 Indian Space (2021). BEARCAT analysis was also performed for Chandrayaan-3 composite and its propulsion and lander module during their lunar phase, though no collision avoidance or plane modification was necessitated. A wider threshold is applied to manoeuvre plan screening to keep an adequate margin in close approach distance for performance deviation. All flyby and lander missions are also included in BEARCAT for a given planetary regime as and when needed.

Post-Mission Disposal

Disposal of GEO Satellites

The unique nature of the geosynchronous altitude of 35786 km makes GEO a precious resource, adding a restriction on the number of satellites that can be placed without

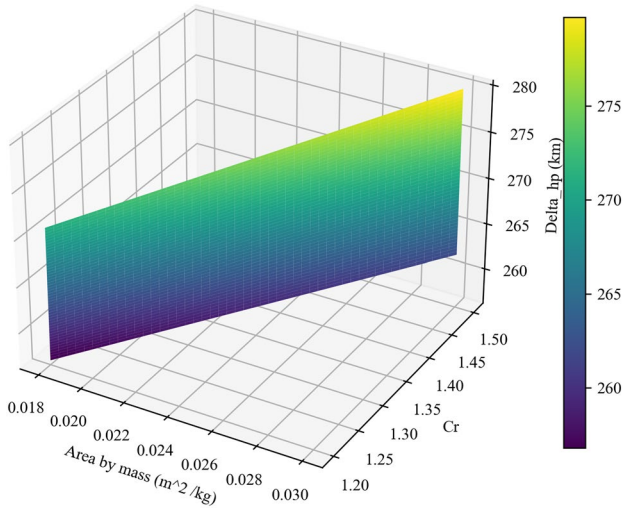

Fig. 9 Recommended increase in perigee altitude for different combinations of C_r and A/M

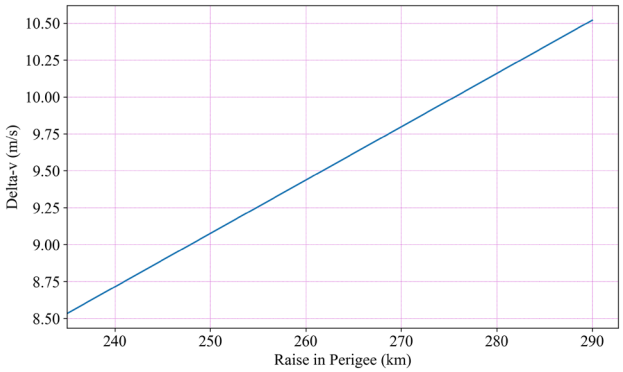

Fig. 10 Net delta-v requirement for PMD of ISRO's GEO satellites

interference in the GEO belt, hence the immediate neighbourhood of GEO, the IADC-defined protected region, needs to be preserved against the generation of space debris. Unlike LEO, there is no natural mechanism for the complete removal of space objects from GEO. The inclination of an uncontrolled GEO object grows up to 15° and again decreases to 0° following a 53-year cycle, while lunisolar gravitational perturbations result in a cyclic build-up of its eccentricity with a 10.4-year cycle. Hence, to preserve the GEO region for sustainable use, objects reaching end-of-life in this region should be re-orbited beyond the GEO-protected region. The disposal orbits need to meet the criterion that they should not interfere with or return to the GEO region due to perturbation forces within the next 100 years.

Criterion-I: As per the IADC and other studies (IADC Working Group 2021), for an object to remain above the GEO region under the influence of perturbation forces for a long period (more than 100 years), the minimum rise in perigee corresponding to the disposal orbit from the GEO altitude is computed by accounting for the 200 km altitude clearance above the GEO belt and the altitude variation due to a) geo-potential and lunisolar effect, the combined contribution is expected to be 35 km, and b) solar radiation pressure effects that depend on area-to-mas ratio (A/M) and coefficient of radiation (C_r). The minimum increase in perigee altitude from the GEO belt (denoted as Δh_{min}), is given by

$$\Delta h_{min} = 235 + 1000 C_r A/M \tag{1}$$

Criterion-II: In addition, the eccentricity of the final orbit should be ≤ 0.003 because the orbital altitude variation depends on the initial eccentricity of the orbit.

Figure 9 shows the required rise in perigee altitude from GEO in km for different combinations of C_r and area-to-mass, which apply to ISRO satellites. The corresponding delta-v required to realize the perigee raise, as shown in Fig. 10, is typically about 10-11 m/s.

Except for a few initial missions, PMD has been carried out for all GEO satellites since the early 1980 s Prasad (2005); Adimurthy and Ganeshan (2006). The operations are planned and executed by Master Control Facility (MCF), Hassan, in synergy with other ISRO entities. The major considerations for PMD of GEO satellites are described next.

Current Operational Practices

For ISRO's GEO satellites, the fuel required for the post-mission re-orbiting to super-synchronous orbits to comply with the IADC recommendations is allocated during mission planning for GEO missions, and the overall PMD strategy is also worked out as part of mission planning. Before the commencement of the PMD, satellite service is migrated to the replacement satellites. Prior intimation and close coordination with the operators of satellites in the neighbouring longitudinal slots is also necessary as the satellite undergoes considerable longitudinal drift once it departs from the geostationary altitude. Command carriers are brought up only during commanding requirements to avoid interference with neighbouring satellites during such drifting phase.

At present, a multiple burn strategy is adopted for the post-mission orbit raising. First, a manoeuvre is conducted to exit from the colocated constellation, wherever applicable, or to circularize the orbit. The orbital height is then increased progressively with paired burns. A perigee burn and an apogee burn separated by half orbit period between them are carried out so that an almost circular intermediate orbit after every second manoeuvre is guaranteed. Even though this strategy takes a longer duration to complete the decommissioning process, it helps for optimum utilization of available propellant to achieve the disposal orbit as per IADC recommendation. In case any unforeseen anomaly or

eventuality terminates the disposal operation prematurely, the last achieved orbit would still have a low eccentricity and achieve the best possible compliance with the IADC guideline. Post re-orbiting to the final circular orbit, the residual propellants are spent through inclination change manoeuvres. This strategy again ensures that the eccentricity of the final orbit is not disturbed and remains within the required 0.003 limit. Re-orbiting, therefore, involves a multiple burn strategy with typically more than 6 burns.

The space object population density in the GEO region is less compared to LEO. A smaller number of operational satellites reside in the vicinity of the GEO longitudinal slot of a given satellite to avoid RF interference. Nevertheless, taking into consideration the growing space object population in GEO, all manoeuvre plans were screened through SOPA to ensure that there were no post-manoeuvre conjunctions with any other space objects for the recent PMD exercises. After re-orbiting, electrical passivation is carried out. An example of PMD of a GEO satellite is presented next.

PMD of GSAT-12

Figure 6 shows a typical altitude raise profile for the disposal of GSAT-12 Indian Space Research (2024). The minimum rise in perigee altitude as per Eq. 1 was approximately 261 km. After the initial circularization, six manoeuvres were carried out for orbit raising, in steps of approximately 116 km altitude during 16–19 March 2023. The burns were executed by firing the West thrusters at perigee and apogee alternately, each 12 h apart. After the seventh manoeuvre on the 19th of March, a super-synchronous orbit of nearly 400 km above GEO was achieved. The left-over fuel was then spent through inclination change manoeuvres (marked as depletion burns in Fig. 11) to avoid any change in the altitude of the already achieved orbit, which was of a very low eccentricity (0.0001). Further increase in altitude would also have imparted excessive westward longitudinal drift, making the satellite go out of the visibility of the Indian ground stations. After the depletion burns (20–22 March), the final passivation manoeuvre was executed by firing the oppositely mounted thrusters to cancel the net thrust without affecting the orbit on 23 March, followed by electrical passivation of the satellite.

Compliance with IADC Guidelines

Except for a few satellites, such as the older satellites like APPLE and the more recently launched GSAT-6A, which could not be re-orbited due to abrupt mission termination, all ISRO GEO satellites have undergone PMD. INSAT-2DT was the first satellite to have successfully undergone a PMD operation in full compliance with the IADC guidelines (Prasad 2005). It is noteworthy that all recent GEO re-orbiting exercises have been 100% compliant, as seen from Table 2. This feat is achieved through meticulous planning, on-orbit operation management, and timely replacement.

Post-Mission Disposal of LEO Objects

Objects passing through LEO such as defunct satellites, spent upper stages, and debris fragments, pose collision risks to operational LEO assets till their orbits decay and re-enter the atmosphere under the influence of various perturbative forces, primarily atmospheric drag. For LEO objects, disposal through direct re-entry into the atmosphere or manoeuvring into an orbit with a shorter orbital lifespan

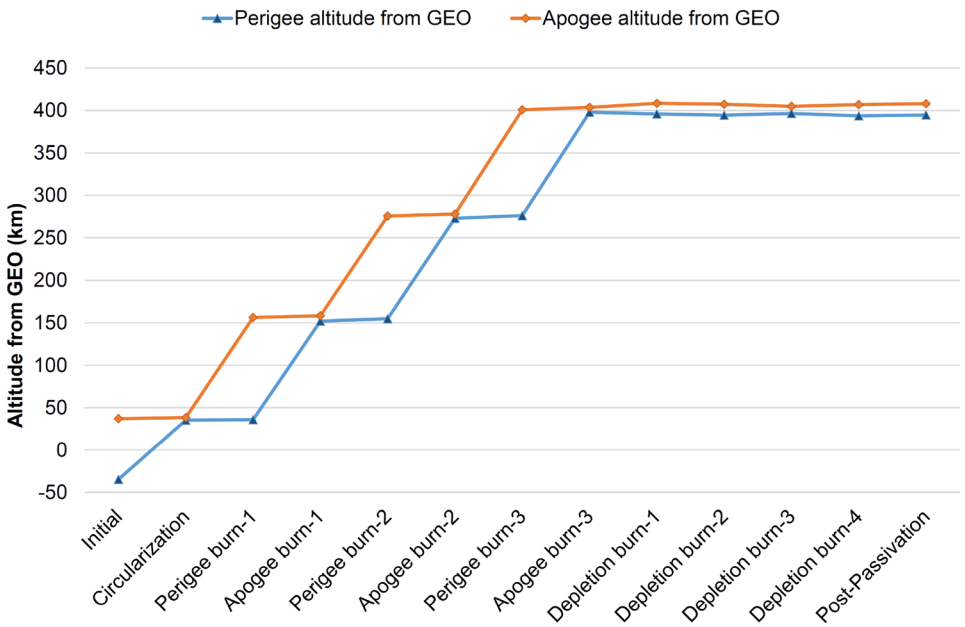

Fig. 11 Variation of perigee and apogee altitude from GEO (35786 km) during the PMD of GSAT-12

Table 2 Achieved post-mission disposal orbits of decommissioned GEO satellites of ISRO (since 2018)

Satellite	Min. perigee raise as per IADC (km)	Realized orbit (apogee x perigee height from GEO)	No. of burns
KALPANA-1	254	567 × 560	3
GSAT-3	265	289 × 285	3
INSAT-4A	271	293 × 288	10
INSAT-4CR	266	301 × 293	10
INSAT-4B	273	384 × 293	11
GSAT-12	261	407 × 394	11

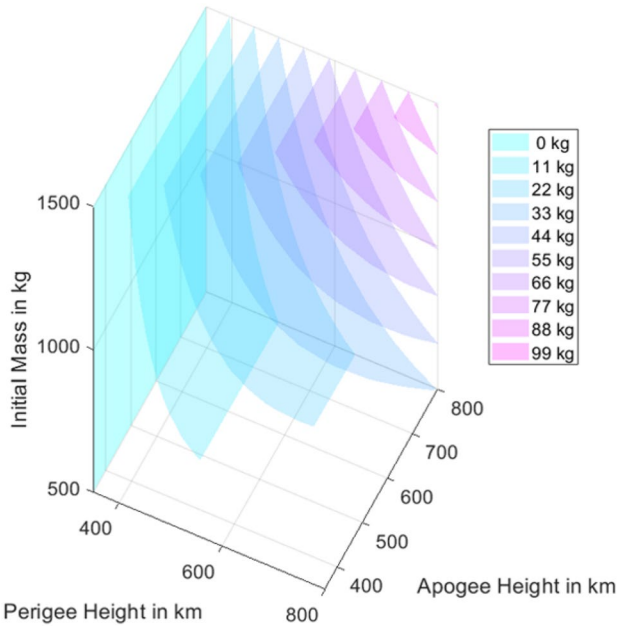

Fig. 12 Fuel mass required for de-orbiting LEO satellites to a final perigee of 350 km altitude for different initial masses of the satellite (shown in z-axis) and initial apogee-perigee altitudes

is recommended. Due to the fuel penalty associated with disposal, 25 years was regarded as a reasonable and appropriate post-mission orbital lifetime limit for LEO objects (IADC Working Group 2021). However, with the proliferation of large constellations and skyrocketing object population, an even shorter lifetime of 5 years is now considered necessary.

Post Mission Disposal of LEO Satellites

Figure 12 shows the fuel mass in kg required (plotted as iso-surfaces) for different combinations of initial apogee and perigee altitude and satellite mass, it is assumed that the end-of-life specific impulse $(I_{sp}) = 180$ s, and the final perigee after de-boost is 350 km. Therefore, typically more than 20 kg of fuel is required to de-boost a satellite of mass 500 kg or higher when the initial orbit is above 600 km altitude. Controlled re-entry is even more fuel expensive as a still lower perigee, preferably below 80 km, needs to be accomplished for guaranteed re-entry over a particular targeted region.

The general strategy for de-orbiting LEO satellites is firing the thrusters in the anti-velocity direction at apogee to reduce the perigee altitude. In certain cases, onboard constraints (such as station visibility during the burn, and intrusion of the Sun into star sensor field-of-views) prevent firing the thrusters exactly at apsis points. Secondly, unlike GEO satellites, instead of a generic strategy, PMD strategies require tailoring according to spacecraft configuration, constraints, altitude regimes, and sometimes, also to meet additional mission requirements. PMD exercises for LEO satellites extend over several months and involve a greater number of manoeuvres because of the limited thrust capabilities and also additional complexities and constraints compared to the GEO satellites. The overall strategy is worked out at the beginning and reviewed by a committee constituted for the PMD of LEO satellites. Subsequently, the exact burn plans for the manoeuvres are refined based on an assessment of thruster performance after post-manoeuvre orbit determination. All the de-orbiting manoeuvres are screened through the conjunction assessment process of SOPA to rule out imminent post-manoeuvre close approach risks. Special care is taken to maintain sufficient separation with crewed space stations like the International Space Stations and the Chinese Space Station while planning the manoeuvres. Now, we briefly present the specific PMD exercises of ISRO's LEO satellite missions. These operations are planned and executed by the team from Spacecraft Operations Area, ISTRAC, in coordination with the mission team of U R Rao Space Centre (URSC), sub-system designers from URSC and Liquid Propulsion Systems Centre (LPSC), and Safe and Sustainable Operations team of ISTRAC.

Cartosat-2 Cartosat-2 was the first ISRO LEO satellite which was de-orbited through a series of perigee reduction manoeuvres. Launched on 10 Jan 2007, the satellite was operational at 630 km altitude till August 2019. The orbital lifetime at the nominal operating altitude would have exceeded 30 years. Moreover, there was leftover fuel of 26 kg on board which posed potential break-up risks. Hence, it was decided to implement a maximal perigee reduction PMD strategy to minimize the post-mission orbital lifetime of the satellite utilizing the available fuel. Starting from March 2020 to February 2021, 31 perigee reduction orbit manoeuvres were executed. With a finally achieved perigee of 380 km, the post-mission lifetime, even under very benign solar activity, was estimated to be less than 5 years (Mukherjee and Anilkumar 2021; Agarwal et al. 2022). Therefore, the PMD was in perfect compliance with the IADC recommended "25-year rule". Figure 13 shows the

progressive reduction in apogee and perigee altitude as a result of the de-orbiting burns. The satellite eventually re-entered the atmosphere on 14th February 2024 Indian Space Research Organisation (2024), within 4 years of the commencement of the PMD.

Microsat-TD Microsat-TD was launched on 10th January 2018 in 378 km orbit and reached its end of the mission by 2019. Its orbital lifetime at this low altitude was only a few months, and hence, already compliant with the "25-year" rule. Nevertheless, the satellite was de-orbited to deplete its leftover fuel of 5 kg. Apart from 8 in-plane manoeuvres to lower perigee, 31 out-of-plane manoeuvres were carried out to prevent orbital decay before the complete utilization of fuel. The satellite re-entered the Earth's atmosphere on November 27, 2020. This de-orbiting provided very useful first-hand experiences for operating at very low altitudes, it required special and dedicated analyses to meet the demands of orbit determination in the presence of a highly variable lower atmospheric environment.

Meghatropiques-1 In a landmark achievement, the Controlled Re-entry of Megha-Tropiques-1 Experiment (CREEM) was successfully conducted on 7 March 2023. Meghatropiques-1 (MT1) was operational in a 20° inclined orbit at 867 km altitude, for which the post-mission life would have been more than 100 years. Though this satellite was not designed for controlled re-entry and had also suffered a few system degradations, the availability of more than 100 kg of left-over fuel presented a unique opportunity to attempt its re-entry within a targeted impact zone (Mukherjee 2023; Mukherjee et al. 2024). This remarkable feat was accomplished through a series of perigee de-boosting, with periods of inactivity interposed to allow the lowering of the orbit through the natural drag-induced decay (see Fig. 14). One perigee raising manoeuvre was also carried out on 19th Feb 2023 to ensure that the orbit did not decay before the required conditions for targeted re-entry were met. The operational experiences of Microsat-TD were effectively leveraged.

The impact zone was finalized based on inputs from the Range Safety Office of Satish Dhawan Space Centre at Sriharikota, after accounting for the downrange uncertainty. An uninhabited zone in the Southern Pacific Ocean was targetted and NOTAM was issued. Based on detailed simulations of the subsystems, the de-orbiting scheme was refined synergistically by different teams from ISRO work centres. The final two burns were executed on 7th March 2023 in successive orbits. The final manoeuvre design was aimed to minimize the operational duration within lower atmospheric regions while ensuring visibility over ISTRAC ground stations during the burns. Based on the last available data acquired during the final burn, it was inferred that the re-entry took place as intended (Indian Space Research 2023). The targeted impact location and the firing points of the last two burns are shown in Fig. 15.

Scatsat-1 Scatsat-1, a microsatellite launched in 2016, was maintained in a 720 km orbit till its payload operation continued up to 2024. While its subsystems were nominally functioning, there was limited fuel available (approximately 8 kg) to de-orbit it below 500 km. Furthermore, taking into account the densely populated orbital bands of Starlink around 550–570 km, it was decided not to de-boost below 590 km to avoid any uncertainty in the post-manoeuvre orbit during the final phase of de-orbiting due to fuel exhaustion. After 10 burns, the remaining burns were planned at intermediate points to meet visibility constraints. The last couple of burns were planned with a shorter burn duration considering the uncertainty in estimated fuel, so that any unexpected end of burn would not result in a marked deviation between the realized and predicted orbit. Two manoeuvre

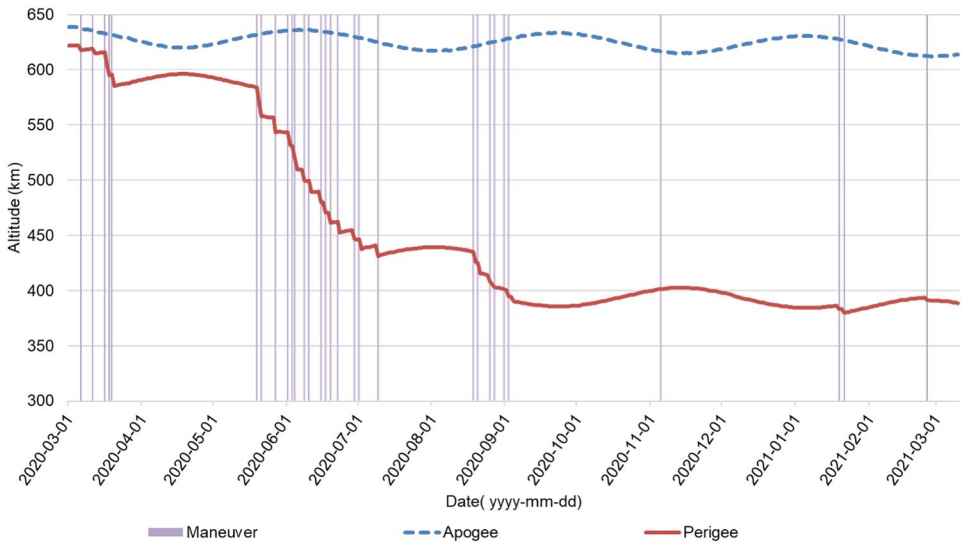

Fig. 13 Apogee and altitude variation for Cartosat-2 during PMD

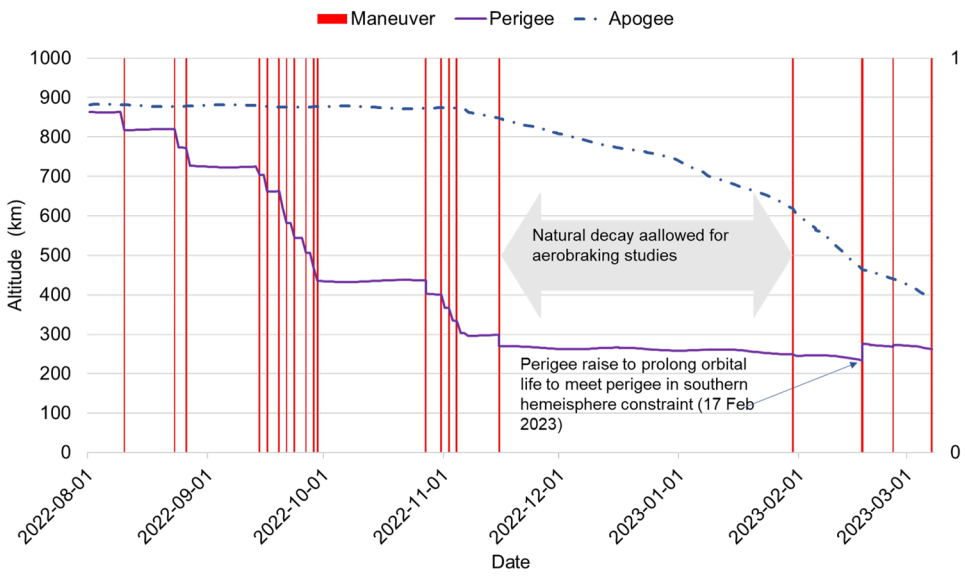

Fig. 14 Apogee and perigee altitude reduction of Meghatropiques-1 during PMD

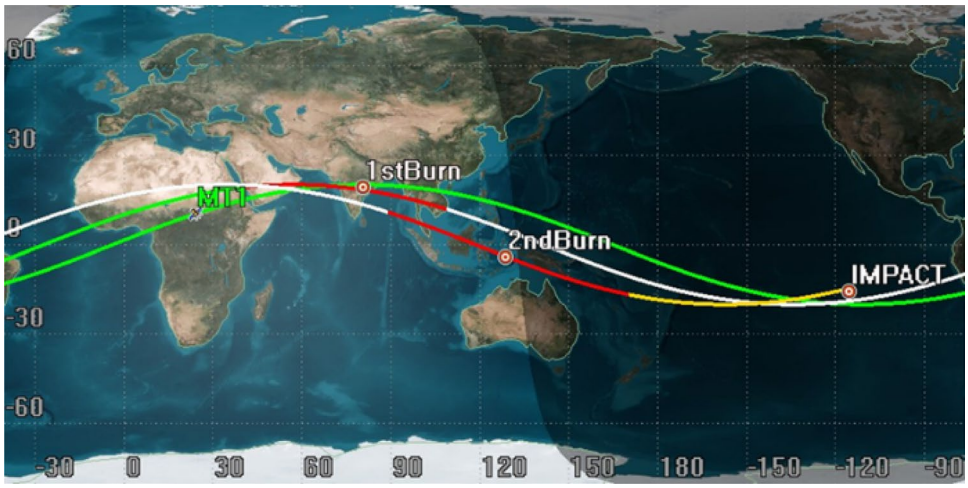

Fig. 15 Estimated impact point and last two burns for the controlled re-entry of MT1

plans had to be reworked based on conjunction screening to avoid potential post-manoeuvrer conjunctions.

During the 12th burn, the fuel was found to be exhausted. Figure 16 shows the altitude reduction achieved as a result of the 12 PMD manoeuvres. The satellite was finally decommissioned in by Sep 2024.

Post Mission Disposal of Rocket Bodies

Since 2002, passivation after payload injection has been implemented for all orbital stages of ISRO LV, which applies to PSLV, GSLV, LVM-3, and the most recent Small Satellite Launch Vehicle (SSLV). We present further details below.

Rocket Bodies Ending Missions in Geostationary Transfer Orbit (GTO)

Post injection, all Geosynchronous Satellite Launch Vehicle (GSLV) and Launch Vehicle Mark-3 (LVM3) rocket bodies are left in GTO, having a very low perigee (usually less than 200 km) altitude. The lift-off time is chosen such that their residual orbital lifetime would be limited, more details are provided in 7.2. The orbital lifetime is usually less than 5 years, in compliance with the 25-year rule (see Table 3).

As of November 2024, only three such rocket bodies namely LVM3-M2, GSLV-F12, and GSLV-F14 stages, remain in orbit. They are expected to re-enter within the next 10 years.

Rocket Bodies Ending Missions in LEO

Most of the PSLV upper stage or the 4th stage, PS4, injected above 600 km altitude have an orbital lifetime greater than 25 years. PS4 restarting capability was demonstrated for the first time in the PSLV-C29 mission on Dec 16, 2015. While the restarting capability enabled injecting multiple payloads in different orbital regimes by a single launch mission, it also aided the de-boosting of the upper stage to

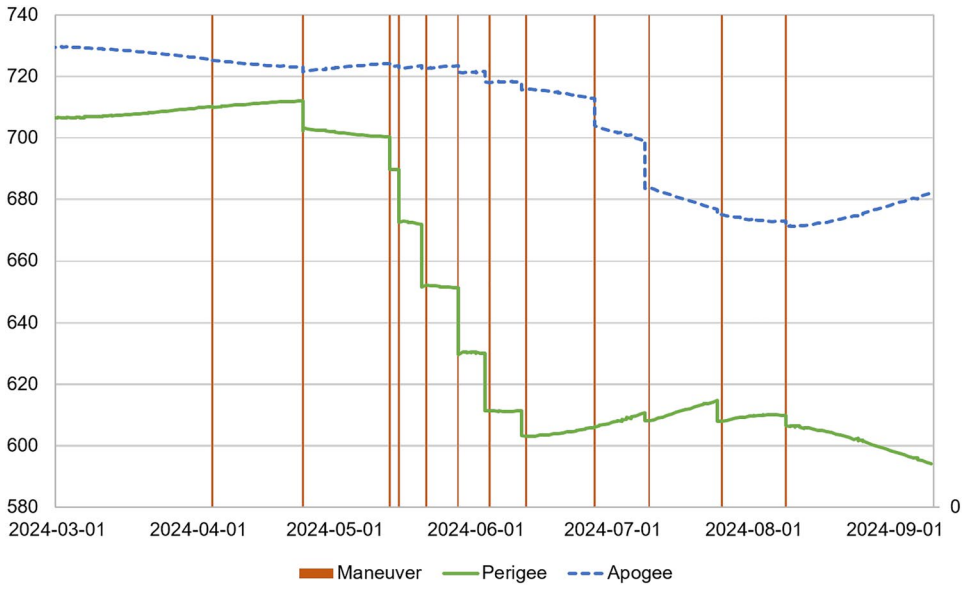

Fig. 16 Apogee and perigee altitude reduction of Scatsat-1 dueing PMD

Table 3 Orbital lifetime of GTO rocket bodies of ISRO

R/B	Launch date	Re-entry date	Orbital life (days)
GSLV-D1	18-04-2001	18-01-2003	640
GSLV-D2	08-05-2003	24-02-2005	658
GSLV-F01	20-09-2004	24-11-2007	1160
GSLV-F04	02-09-2007	08-02-2011	1255
GSLV-D5	05-01-2014	08-06-2014	154
GSLV-D6	27-08-2015	02-03-2018	918
GSLV-F05	08-09-2016	29-04-2019	963
GSLV-F09	05-05-2017	10-10-2017	158
LVM3-D1	05-06-2017	08-02-2018	248
GSLV-F08	29-03-2018	04-12-2019	615
LVM3-D2	14-11-2018	12-05-2019	179
GSLV-F11	19-12-2018	05-04-2019	107
LVM3-M1	22-07-2019	16-10-2019	86
LVM3-M3	26-03-2023	14-06-2024	446
LVM3-M4	14-07-2023	15-11-2023	124

a lower orbit thereby limiting its residual orbital lifetime. Such de-orbiting involves typically two restarts through an automated sequencer at perigee and apogee for optimal fuel usage following the Hohmann principle, control thrusters are also used. For PSLV-C38 and PSLV-40 missions, the PS4 stages were de-orbited to around 350 km altitude. Figure 17 shows the orbital decay for the PSLV-C40 mission. Consequently, both of the PS4s re-entered the atmosphere in approximately one year after their launches. PSLV-C45 was also de-orbited through multiple restarts. On April 1, 2019, it launched the main payload EMISAT in an orbit of 748 km altitude, then injected the rest of the 28 customer satellites at around 505 km altitude after two engine restarts. The upper stage was further de-orbited to an orbit of 485 km altitude, it finally re-entered the atmosphere on 30 Jun 2024.

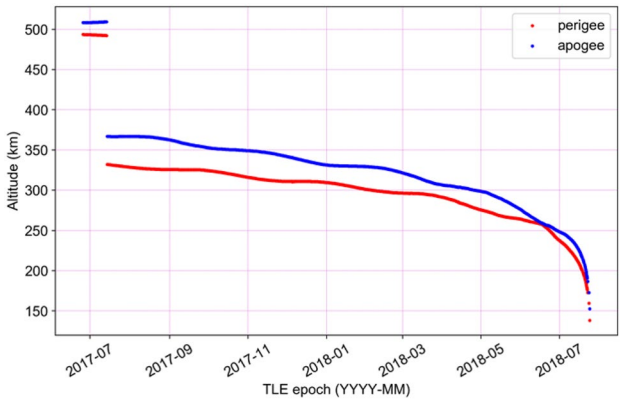

Fig. 17 De-boost and subsequent orbital decay of PSLV-C40 upper stage (TLE data source: Space-Track)

Similar de-boosting was done for PSLV-C56 and PSLV-C58/XpoSat mission was also de-boosted below 350 km altitude. Both the rocket stages re-entered the atmosphere within approximately one month after the launch (Indian 2024).

PSLV Orbital Experimental Module (POEM)

After de-boosting and passivation, PSLV upper stages can also be used as an orbital platform hosting non-separable payloads. Earlier PSLV-C28 and PSLV-C44 missions hosted such payloads. This strategy provides opportunities for a new entrant to the space sector to gain the required on-orbit experience for technology demonstration. In general, such a demo mission typically lasts for a short duration of a few months and proper PMD for such smaller platforms is often not feasible due to on-orbit failures. Therefore, by reducing the total number of objects in space, this innovative

approach allows an emergent space actor to test and qualify new technologies without compromising sustainability requirements. To date, three such POEM missions have been successfully flown on PSLV-C53, PSLV-C54, and PSLV-C58 upper stages.

Passivation

Passivation or removal of active energy sources at end-of-life for a spacecraft or launch vehicle is an essential measure to minimise the risk of post-mission break-ups. Passivation typically involves the expulsion of residual propellants by burning or venting, discharging batteries, releasing pressurized fluids, safing unused destruct devices, etc.

Passivation of Upper Stages of Launch Vehicles

On 19th December 2001, the upper stage of PSLV-C3 underwent a break-up generating 371 catalogued debris. While the procedures for passivation were already being worked out, this incident provided an impetus for its immediate implementation from 2002 onwards as a standard practice for all ISRO launch vehicles (Prasad 2005). Currently, all PSLV's final stage with Earth-storable liquid propellants, the cryogenic upper stage (CUS) of GSLV and LVM3 with liquid hydrogen and liquid oxyfen as propellants, and the velocity trimming module (VTM) of SSLV are passivated after payload injection.

Passivation of Spacecraft

For spacecraft, strategy is implemented on a case-by-case basis based on the energy sources but techniques like the discharge of batteries, the release of pressurized fluids, the safing of unused destruct devices, etc. are usually implemented. Usually, any residual propellant is depleted to lower the orbit for LEO satellites to reduce its orbital life. After re-orbiting the residual propellant is passivated through depletion (by inclination change manoeuvre) and venting. As a part of electrical passivation, all of the rotating devices (momentum wheels, reaction wheels, gyros, solar array driving mechanism) are turned off. On-board batteries are discharged and disconnected from the solar panels to minimize the break-up risk due to overcharging. For symmetrically deployed solar panels, the panels are aligned in orthogonal configuration to minimize aspect area. This arrangement ensures minimal power generation as well as minimal solar radiation pressure-related orbital perturbation that might cause the orbital altitude to decay and encroach into the GEO-protected region. Finally, all transmitters are switched off before decommissioning the spacecraft to avoid RF interference.

Other Measures Adopted for Space Debris Mitigation

Other measures for space debris mitigation are presented in this section.

Minimising Release of Debris and Preventing Accidental Break-Ups During Normal Operation

All ISRO launch vehicle and satellite projects incorporate adequate safety measures to minimise any possibility of system failure leading to accidental break-up during mission life, which undergo rigorous Failure Mode and Effects Analysis and multiple reviews. The components are designed to be contained within the spacecraft after deployment. The material and components are chosen to avoid degeneration and disintegration under on-orbit environmental conditions such as prolonged exposure to radiation, erosion by atomic oxygen, thermal cycling etc. during the mission life. Launch vehicles are designed to ensure that minimal debris objects are left in orbit after the payload injection. Components like separation systems, external harnesses, bolts, nuts, puffs etc. are designed to be contained within the rocket body after satellite separation. Only the upper stage(s) required to inject the payload(s) in the designated orbit, and the essential adapter(s) for multiple satellite launches are left in orbit after the injection of payloads.

Shielding

A millimetre-sized debris impact is unlikely to be catastrophic but the the debris can perforate the structure and cause problems with batteries or other critical components which may lead to a premature termination of the mission life. In such a case, there should be proper protection for the asset from such small debris impact through active and passive means. Active protection uses sensors to provide a warning of impact and then protect its critical components or flag a signal to move the spacecraft to avoid the potential impact. Passive protection schemes like the shielding of a spacecraft or its critical components can help safeguard a space asset against small uncatalogued objects. ISRO has also undertaken activities related to shielding to protect against micrometeoroids and orbital debris risk. For upcoming missions like Gaganyaaan and NISAR, the probability of no penetration (PNP) estimation and debris shield design for all regions to meet PNP specifications. Ballistic Limit Equations (BLE) available in the literature are used for

shield design and validated through Hydrocode simulations. Further validation through Hypervelocity impact tests are also on the anvil.

Space Debris Related Studies and Research Activities

In this section, we present the various studies and research activities undertaken in the area of space debris to ensure the long-term sustainability of outer space activities.

Selection of Less Collision-Risk Prone Mission Orbit

For non-GSO satellite missions of ISRO, the necessary analysis is carried out to select a nominal orbit away from the already known high-flux density region in space to avoid frequent conjunction threats, as long as such a choice does not compromise payload goals or violate mission constraints. Altitude variation due to the perturbations, primarily induced by the oblateness of the Earth is also accounted for in such analyses.

Minimization of GTO Lifetime

The geostationary transfer orbit (GTO) is a highly eccentric orbit with the perigee normally at low altitudes (170–800 km) and the apogee near the geostationary altitude of around 36000 km. The evolution of objects in GTO orbits is determined by a complex interplay of atmospheric drag and lunisolar gravity and such orbits are characterized by periodic changes in perigee altitudes. The initial orientation of the orbit just after the launch with respect to the Sun and the Moon predominantly determines the subsequent orbital evolution. As a result, the lifetime of a GTO object can vary from a few months to several decades, depending on the time of its launch (Sharma et al. 2004). However, one cannot always rely on natural perturbations to limit the orbital lifetime, as the launch time of a geostationary satellite is dictated by many other factors like thermal aspects and eclipse time. Nevertheless, the lifetime in GTO can be significantly reduced through appropriate choice of the initial perigee altitude and launch time. As a result, all GTO stages have limited orbital lifetime, as discussed in 4.3.1.

Atmospheric Re-entry Analysis

Accurate prediction of the re-entry time for uncontrolled space objects is challenging due to various factors influencing the atmospheric re-entry process. A numerical method is typically employed for the re-entry time prediction, it involves gathering data in terms of two-line element sets (TLEs) or state vectors (SV) from multiple sources and combining them using sophisticated algorithms, such as the Kalman filter, to improve the object's orbit estimation accuracy. Once an estimate of orbit is made, a high-fidelity orbit propagator which solves the governing differential equation of orbital motion in the presence of various perturbations is used to estimate the re-entry time and location. The ballistic coefficient, representing the ratio of the object's mass to its drag characteristics, is a crucial parameter in re-entry prediction. Estimating the ballistic coefficient for uncontrolled space objects is challenging due to their irregular shapes, unknown masses, and uncertain aerodynamic properties. Atmospheric models accounting for various factors such as solar activity and seasonal variations play a crucial role in orbit propagation as the drag experienced by an object depends on the density of the surrounding air.

Over the past couple of decades, ISRO has developed several methodologies for re-entry time and impact location prediction of space objects making uncontrolled atmospheric re-entry. All these methods approach the re-entry prediction problem as an optimal initial parameter estimation problem, such as the Constant Gain Kalman Filter Approach (Anilkumar et al. 2007), Response Surface Methodology with Genetic Algorithm (RSMGA), STKOptim (Optimization using System Tool Kit), STKLtOptim (Lifetime optimization with System Tool Kit), ABPRO (Automated Back Propagation) (Sharma et al. 2009; Dutt et al. 2023; Gupta and Anilkumar 2015). Recognizing the potential hazards posed by the uncontrolled re-entry of certain space objects, e.g., the Soviet Cosmos 954 spacecraft (January 1978), the U.S. Skylab space station (July 1979), and the Soviet Salyut 7- Cosmos 1686 space station (February 1991), some members of the IADC participated in an exchange of information during the final days of the orbital life of the Soviet Cosmos 398 spacecraft in December 1995. The success of this exercise led to the adoption by IADC to conduct at least one test campaign annually. The re-entry object for each test campaign is selected based on a common agreement of IADC members. Potential re-entry objects should be of sufficient size (more than 1 m^2) and typically of sufficient inclination to be tracked by all IADC members. ISRO actively participates in these annual IADC re-entry campaigns by providing estimates of the time of re-entry of the test objects. ISRO's submitted predictions for the 2024 annual re-entry campaign with ERS-02 as the test object are represented in Fig. 18.

It clearly shows the reduction in uncertainty in prediction with the approaching re-entry epoch.

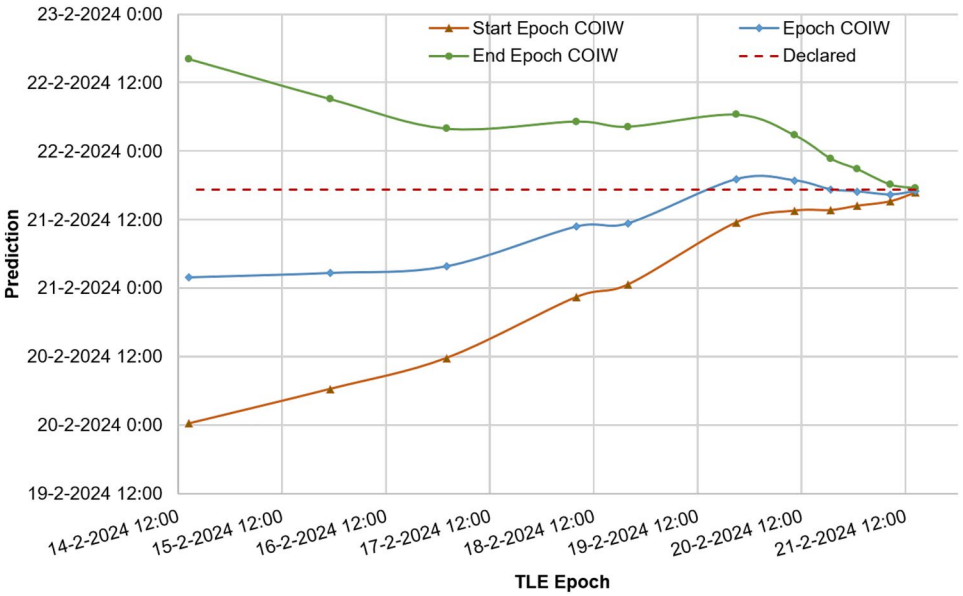

Fig. 18 ERS-02 re-entry predictions submitted by ISRO for 2024 annual IADC campaign (COIW: centre of impact window)

Estimation of Re-entry Risks

ISRO has developed in-house software packages for aero-thermal break-up and re-entry risk estimation, namely Debris Re-entry Thermal Analysis Package (DRETAP). It is aimed to estimate aerodynamic heat flux levels, the thermal response of an object re-entering the Earth's atmosphere and its altitude of demise to assess their potential risk on ground impact. The inputs for the analysis are geometry, structural details, thermo-physical properties, motion and re-entry trajectories of the re-entering object along with the atmospheric model. Engineering methods are used to estimate aerodynamic heat flux, then the thermal response is computed by heat conduction equation for a multi-layer structure, after imposing suitable boundary conditions and provisions for modelling charring/ablation/melting at the surface. The tool has been used for aerothermal break-up and survivability analysis for LEO satellites re-entering the atmosphere. Most of the components are found to perish due to the intense aero thermal heating, only high heat-resistant components like gas bottles, fuel tanks, thruster nozzles, titanium spacers, etc. are found to survive.

Debris Environmental Modelling

Objects less than 10 cm are difficult to track individually, hence a statistical estimation is made of the population density based on measurements. These density models are generated over the years with cumulative measurements. The centimetre-sized objects are derived from the dedicated radar campaign. The encountered sub-millimetre debris population are inferred from the analysis of retrieved surfaces and in-situ impact sensors. The population is also characterized based on the ground-based simulations of hypervelocity collisions with satellite and rocket bodies, and ground-based simulations of explosive fragmentations. These data generated from experiments and campaigns are used for validation and improvement of the debris flux models which can be deterministic or statistical in type or a combination. Such models are useful in risk and damage assessment, prediction of debris detection rates for measurements, collision avoidance measures, and the analysis of the effectiveness of debris mitigation measures. Several source mechanisms are considered, which include launches, break-ups produced by explosions and collisions, material separation due to ageing, solid motor firing manoeuvres etc. Sink mechanisms include orbital decay due to atmospheric drag and other perturbations, retrieval from orbits, and deorbiting etc. The episodic variations of the dynamic small debris population are captured through short-term and long-term models. Since 2000 s, several models have been developed in-house for analysing fragmentation events and associated studies have been conducted by Anil Kumar et al. Anilkumar (2005); Anil Kumar et al. (2005); Ananthasayanam et al. (2006a, 2006b); Anilkumar and Reddy (2009).

Capacity Building for Space Situational Awareness (SSA)

Space Situational Awareness (SSA) involves a comprehensive knowledge, understanding, and continual awareness of the current status and future evolution of the space environment. SSA capabilities are crucial for spaceflight safety, namely timely collision threat detection, accurate analysis of the situation for mitigating the threats, planning orbital manoeuvrers in a safe manner. SSA also plays a major role

in assessing the compliance with the SDMG. We now discuss two major areas of SSA which are relevant to mitigating space debris.

Space Debris Observation

One of the major areas of space debris studies and research involves the identification and characterization of the space object. Measurements are done with the help of ground-based radars and telescopes. Ground-based radars are well suited to observe space objects in LEO orbits because of all-weather day-night observation capability. Radar power budget and operating wavelength are the limiting factors for the detection of small objects at long ranges. Optical facilities can detect debris when it is sunlit and the background sky is dark. For objects in geosynchronous orbit, optical observations can be continued during the entire night. Debris tracking capabilities of optical telescopes in the LEO region are limited to one to two hours a day during the twilight due to the availability of sunlight for illuminating the object. Higher angular rate of LEO objects results in faster transit of objects which also limits the duration of observation. However, with emerging technologies, optical telescopes can also be used to track objects in LEO. ISRO has undertaken project NETRA (NEtwork for Space Objects Tracking and Analysis) to establish an independent end-to-end capability to detect, identify, track, and catalogue space objects, including spaced debris. The main three elements of the project are one phased-array, multi-object tracking Radar; one optical telescope capable of tracking a 40 cm object in geostationary orbit; and a Control Centre, which is already operational at Bengaluru, Karnataka and functions as a hub of all SSA related activities, including observational data processing, object identification and cataloguing. The expansion of the observational network is also envisaged by adding more telescopes and radars.

Space Weather Studies

Space Weather, mainly governed by solar activities, plays a major role in the orbital evolution of space objects. During intense solar activities, the emitted radiation causes the Joule heating of Earth's upper atmosphere and consequent expansion, which in turn increases the drag experienced by a space object. The study of space weather involves probing the magnetic field structures on the sun and solar wind disturbances, investigating the Solar and interplanetary origin of geomagnetic disturbances, the study of day-to-day variability in the terrestrial magnetosphere-ionosphere-atmosphere system and understanding the effect of these disturbances on space-based technological systems and their subsequent results. In addition to contributing to global scientific research, ISRO is actively engaged in studying space weather to safeguard both space-based and ground-based infrastructure. Detailed modelling of the sunspot cycles and predict its behaviour has also been carried out by Sabarinath et al. Sabarinath and Anilkumar (2008, 2011) . India's first space-based solar observatory, Aditya-L1, is designed to observe the Sun and its impact on space weather. As part of space situational activities, continuous watch is kept on solar activity and geomagnetic storms to alert the spacecraft operations teams and mitigate the impact of space weather on India's space assets. The Indian Network for Space Weather Impact Monitoring (INSWIM) is a proposed network of instruments across India that aims to monitor space weather parameters in real time, with a focus on ionospheric disturbances, geomagnetic variations, and their effects on communication and navigation systems. ISRO's systems, such as the GPS-aided Geo Augmented Navigation (GAGAN) and the Navigation with Indian constellation system (NavIC), play a vital role in studying ionospheric variations triggered by solar activity. ISRO also conducts research and development to model and analyze data for simulating solar and magnetospheric interactions.

International Cooperation, Policy Aspects, and Awareness Raising

Recognising the importance of international cooperation to ensure that space operations are conducted to minimise the risk of instability in the outer space environment, ISRO engages with other space-faring agencies through data sharing, knowledge sharing and technological collaborations. ISRO has been a member of IADC since 1996 and regularly participates in the annual IADC meetings, effectively contributing to the proceedings of its working groups as well as the Steering Group. ISRO engages in the activities of the IAA Space Debris Working Group and is a member of the IAF STM committee that actively contributes to a better understanding of issues related to Space Traffic Management. Additionally, ISRO is a member of the ISO space debris working group contributing towards the development and effective implementation of space debris mitigation guidelines. As a leading space-faring agency, ISRO will continue to be at the forefront of steering the course of technological development as well as policies related to space debris mitigation and remediation. At present, there are no binding international laws that explicitly prohibit the generation of space debris. The UN-COPUOS guidelines stress that member states and international organisations should voluntarily adopt measures, through national or other relevant frameworks, to implement these guidelines to the greatest extent possible. Consequently, the effectiveness of these guidelines

largely relies on voluntary adherence by individual countries, underpinned by appropriate policies, norms, and procedures that all space-related entities within those countries must follow. In 2023, India introduced its Space Policy to foster private sector participation (Department of Space 2023), it also emphasises developing cost-effective methods for space debris mitigation through innovative approaches. The Indian National Space Promotion and Authorization Center (IN-SPACe) ensures that space debris mitigation requirements, particularly those related to PMD and collision avoidance, are met during the registration process by both government and private entities (Indian National Space 2024). IS^{4}OM provides the necessary technical support for compliance assessments and collaborates with emerging private operators through IN-SPACe to guide them through the authorization and registration processes, as needed.

Apart from the efforts involved, PMD incurs additional costs, which are often viewed as a penalty and prove to be a deterrent for implementation, especially by non-traditional space actors. However, it needs to be impressed upon and realized by all space-faring entities that space, though vast in expanse, is a finite resource to be utilized judiciously. Focusing on individual, short-term gains alone would eventually jeopardize the sustainability of continued operation in outer space. Unabated accumulation of debris would eventually make the triggering of Kessler's syndrome a reality. Therefore, awareness raising on the fragility of the space environment and the urgent need for implementation of SDMG is of utmost importance.

As part of such awareness raising, in 2024, ISRO in association with the Astronomical Society of India organized an international workshop on "SSA & STM – Growing Concerns on Space Environment", during 11–13 Jan 2023 which was the first of its kind in India. The event was attended by about 400 participants and leading experts in the areas of space debris research delivered talks on a wide range of topics, including PMD practices. Based on the overwhelmingly positive response from the student community, a three-day student workshop for SSA-STM in October 2023 where the crucial role of PMD in cleaning the space environment for its sustainable utilization was repeatedly emphasized. The International Conference on Spacecraft Mission Operations held during 8–9 June 2023, also had space debris mitigation as one of the key themes.

Limitations, Challenges, and Lessons Learnt

We now discuss the limitations, criticalities, challenges faced and lessons learnt during the implementation of SDMG.

Current Limitations and Challenges Faced

PMD of GEO Satellite

For post-mission disposal of GEO satellites, apart from the uncertainty in propellant estimation, the propellant allocated for PMD sometimes gets utilized in station keeping due to a delay in decommissioning. In case a satellite does not have sufficient propellant, the required Δv needs to be imparted through multiple, small pulse-width firings. In some cases, depletion of one of the propellants, usually oxidizer, results in attitude error build-up. Improper attitude hold is likely to result in an unexpected termination of the burn, lowering the PMD success probability. Proper functioning of the propulsion and attitude control system is essential for manoeuvring a satellite at end-of-life. System failures may occur due to ageing effects because the on-orbit operational duration often exceeds the designed life. For example, failure of one block of thrusters at one side (such as the failure of West side thrusters for orbit raising) adds severe limitations. In some cases, where West thrusters were not usable, East Thrusters were fired without any rotation to bring both perigee and apogee below the GEO altitude to relocate away from the GEO protected region and thereby minimize the collision risk with operational GEO objects to the best possible extent. Satellite attitude control becomes extremely difficult in case of actuators and sensors (such as momentum/ reaction wheels and dynamically tuned gyroscopes) failures. Therefore, initiating PMD at the end of the planned design life plays a key role in PMD success.

PMD of LEO Satellites

For PMD of LEO satellites, one of the major challenges arises due to the non-nominal functioning or performance deviation of the subsystems during the orbit-lowering process, because these systems are designed to function nominally at the particular altitude specific to the operational life of the mission. In this context, the lessons learnt during Microsat-TD and Cartosat-1 missions proved very useful in tuning the on-board parameters as well as ground alarm limits, wherever applicable. Compensating for the atmospheric drag-induced disturbance on the platform and high antenna tracking rate at lower perigee also add to operational complexities. Unlike GEO satellites, the LEO spacecraft bus is usually "tied" with the batteries and there is no provision to disconnect the batteries from solar arrays. Hence, complete electrical passivation through disconnecting all sources of energy to the subsystems becomes another challenge. For controlled re-entry, this is not an issue as the satellite is aimed for demise with a short orbital life. However, for satellites that terminate PMD at an altitude where the orbit

takes a few months to years to decay and re-enter the atmosphere, battery charging needs to be prevented by ensuring that the satellite's tumbling motion would not generate adequate power.

Mission Extension Considerations

The main dilemma arises when beyond the stipulated mission life, the payloads continue to perform nominally while the subsystems start showing degraded performance. Extending mission Based on the lessons learnt from the past PMD exercises, a few inputs have been derived for improving the compliance for future LEO missions. In line with the practice followed for GEO missions, the requisite fuel needs to be allocated for post-mission de-orbiting at the design stage. The mission life of a satellite should be extended only after an assessment of system health, fuel availability, and redundancy aspects to ensure that the capability of successfully conducting PMD at end-of-life is not compromised due to any system failure. It is planned to dispose of LEO satellite and PSLV orbital stages through controlled re-entry wherever feasible. Fuel required for PMD is earmarked in the upcoming LEO missions, especially those planned to be operated above 600 km altitude.

Collision Avoidance and Inter-Operator Coordination

For collision avoidance, the present mode of inter-operator coordination is primarily through the exchange of e-mails and is inadequate to address the overwhelming increase in the number of conjunctions anticipated in future. The time of performing a CAM is often decided based on a trade-off between operational feasibility and accuracy of risk estimation. There is a need to improve and enhance the existing mechanisms and procedures to facilitate timely and efficient communication between operators in case of a close conjunction. The lack of information to contact spacecraft operators also proves to be a major challenge to initiate the requisite coordination and data exchange for collision risk mitigation.

Challenges Due to Large Constellations

Low Earth Orbits are becoming increasingly congested due to multiple large constellations of satellites. Currently, there exists no limit on the number of satellites that can be launched in a constellation. As a result, constellations comprising thousands of satellites are proposed and already being deployed in LEO, increasing the collision risks in the immediate vicinity of their orbital shells by many folds. There are significant operational penalties for ensuring the safety of spaceflight in the presence of large constellations. Apart from processing a large volume of ephemerides for conjunction assessment, intensive coordination is required to resolve conjunctions for a large number of active satellites, usually equipped with low-thrust manoeuvrability, making the usage of operational ephemerides essential for meaningful situational assessments. Deployment of multiple large constellations would result in a non-trivial number of failed satellites, adding to the already dense population of space debris in LEO. The streaks caused by the transits of large constellations satellites also degrade the detection capability of ground-based optical telescopes.

Challenges Due to Small Satellites

Another challenge arises due to the increasing preference to use small satellite platforms, as they provide an attractive option for new space actors to start space ventures. Small satellites are also preferred to build a distributed, more resilient space system. Such satellites typically lack propulsion for manoeuvring to mitigate collision risk, as well as unique identifiability and means for tracking. Hence, they are often difficult to track as well as to identify immediately after launch, especially when injected in batches, and the onus of collision avoidance falls single-handedly on the owner/operators of manoeuvrable satellites. The benefits of incorporating features for trackability and unique identifiability need to be impressed upon the small satellite operators through suitable awareness-raising mechanisms. The requirements of trackability could be included in the relevant national space regulations pertaining to space debris mitigation. As many of the small satellites are being built by academia, they can be encouraged to develop and adopt measures, either active or passive, that can improve trackability and unique identifiability.

The lack of relevant data also poses challenges to the accuracy of analysis. For example, the accuracy of uncontrolled re-entry prediction can be improved by the availability of top-level structural and mass details of the re-entering objects.

Lessons Learnt

The lessons learnt during the implementation of SDMG are summarised below:

- For spaceflight safety, establishing points of contact a priori among agencies helps establish authenticity of communication and also enables safe and expedited exchange of relevant information towards collision risk mitigation.
- It is always better to absorb the CAM requirements in regular orbit maintenance manoeuvres, wherever

feasible, for optimum ground and onboard resource utilisation. Identifying conjunctions a few days in advance with a larger screening volume and monitoring the evolution of the conjunction situation with ephemeris updates to check consistency is essential for this purpose. In practice, often the conjunctions cease to be within the critical threshold as the TCA approaches, eliminating the need to perform CAM. Hence, the final go/no-go for CAM should be no earlier than 24 h before the TCA to reduce orbit propagation error and ensure the availability of the latest orbital information. It should be planned no later than the last but one command upload opportunity.

- Wider thresholds should be applied for conjunction assessment in case of any manoeuvre of a primary/secondary object to account for possible dispersions. Orbital data of secondary should be disregarded if it is not updated within 24 h. In case the secondary is an active satellite, it is essential to coordinate with the operators of the active satellite and exchange orbital information/manoeuvre plans.
- While planning any manoeuvre, the expected post-manoeuvre trajectory should be screened through a conjunction assessment process to rule out close conjunctions after the manoeuvre.
- To avoid launch-COLA gap (the gap in conjunction assessment between injection and proper orbit determination/OD), the analysis interval of LV-COLA is to be extended to the expected availability of OD and also the preliminary orbit estimate derived from LV navigational solution at injection can be used.
- For post-mission disposal, as fuel nears depletion, shorter duration burns with ground station visibility should be planned.
- For controlled re-entry, operating in lower altitude regions should limited as much as possible to avoid associated complexities (increased aerodynamic disturbance, higher antenna tracking rates, etc.).

Future Roadmap

Now we discuss the future roadmap for better compliance with the SDMG.

Debris-Free Space Missions

Debris Free Space Mission (DFSM) marks another key initiative spearheaded by ISRO for sustainability (Indian Space 2024b). The DFSM initiative was declared by the Chairman, ISRO, during the inaugural opening plenary of the 42nd Annual Meet of the Inter-Agency Space Debris Coordination Committee (IADC), held in Bengaluru on April 16, 2024. DFSM aims to achieve debris-free space missions by all Indian space actors, both governmental and non-governmental, by 2030. It also encourages other state space actors to adopt similar practices to ensure the long-term sustainability of outer space. It is planned to present DFSM to the international community and other state-space actors to encourage global participation. The Department of Space will ensure the implementation of DFSM by all Indian space actors through meticulous design and execution of the following guidelines:

a) Avoid debris generation during the operational life of satellites and launch vehicles, as well as during the post-mission disposal phase.
b) Avoid on-orbit collisions and break-ups of satellites and launch vehicles by conducting failure mode studies, implementing redundant systems, and designing missions with high reliability.
c) Avoid intentional break-ups that may lead to long-lived debris.
d) Comply with the post-mission disposal guidelines, ensuring a success probability of over 99%. This includes controlled re-entry or de-orbiting to a lower orbit with less than 5 years of residual orbital life for rocket bodies and spacecraft at the end of their operational life.

By 2030, it is envisaged to plan and operate all Indian satellite and launch vehicle missions with the following considerations:

a) Making special considerations for human spaceflight safety, such as avoiding orbital transfers within the 400 km ± 30 km band designated for human space missions.
b) Ensuring trackability, identifiability, and manoeuvrability of all satellites throughout their mission phases.
c) Recommending mission extensions for spacecraft only after thorough assessments of system health, safety, and readiness for post-mission disposal.
d) Enhancing coordination and data sharing at national and international levels to support safe and sustainable operations.

The initiative also emphasizes capacity building for space object tracking and monitoring and advancing research on innovative techniques for long-term sustainability in outer space activities. Implementation of the DFSM initiative will begin in 2025, focusing on mission planning and design. This will include selecting orbital slots with minimal collision risks, budgeting fuel for post-mission disposals,

planning trajectories for controlled re-entry or de-orbiting, and ensuring system reliability. IS^{4}OM will lead the efforts for its implementation, in collaboration with other entities of the Department of Space. This initiative is yet another testimony to India's commitment to sustainable space operations and aligns with global efforts to curtail space debris growth.

Areas of Further Research

Space debris provides an ample scope for further technical research in the areas of shielding, collision avoidance, active debris removal (ADR), LEO end-of-life disposition, passivation, re-entry disposal, etc. For shielding, experimental studies on hypervelocity impact, materials research for bumper design, in addition to theoretical and experimental studies, are important topics for investigation. Theoretical models and engineering analyses for cost-effective passivation methods are of great technological significance. Statistical risk analysis models for fragmentation and re-entry risks also offer ample scope for research. Further studies on thermal degradation of spacecraft and material survival during re-entry are needed to make more precise predictions and evaluations of re-entry risk.

Space Situational Awareness forms the bedrock of all space sustainability efforts including mitigation. The steep increase in the number of space objects demands heightened SSA. India's unique geographical location needs to be leveraged to emerge as the key contributor to the global efforts for tracking and monitoring the ever-increasing number of space objects. Self-reliant tracking capability requires the establishment of indigenously developed radars and optical telescopes. Such activities have already been initiated and will be pursued in future.

Several studies have shown that in addition to space debris mitigation, is imperative to stabilise the growth of the space debris population. ADR essentially involves the removal/relocation of debris by active means (instead of relying on passive, natural perturbative forces for its removal) from a highly utilised regime and serves as a permanent solution to space debris issues. While several attempts to demonstrate ADR have taken place world-wide over the past two decades, there has been limited success, primarily because of the complexities involved in capturing non-cooperative targets. With the advancement of technologies and growing congestion due to space debris, ADR is expected to become a mainstream activity in future. At present, various activities in the field of space robotics, rendezvous proximity operations, vision-based navigation and related sensors etc. are in progress within ISRO. It is envisaged to utilise these capabilities and leverage the experiences gained from the upcoming Space Docking Experiment (SPADEX) missions for ADR demonstration in future.

Across the globe, the aerospace community is actively engaged in assessing the effectiveness and cost-efficiency of standard mitigation strategies. Long-term environmental models play a crucial role in supporting these efforts. Additionally, focussed initiatives are necessary to develop methods for accurately measuring and estimating existing space debris, particularly in the sub-centimetre range. Furthermore, the rapid expansion of large satellite constellations, each consisting of hundreds or even thousands of satellites, presents significant challenges due to the increased number of objects and resulting congestion. Innovative technological solutions must be devised to ensure the sustainability of space-based operations in this increasingly crowded environment.

Conclusion

Given the ubiquitous applications of space technology in day-to-day life, it is of utmost importance to preserve outer space for continued utilisation by the current and future generations. Adopting space debris mitigation and remediation measures is, therefore, essential to reduce the creation of new debris and actively remove existing debris to maintain a stable and safe space environment. Till remediation by on-orbit servicing and active debris removal gain sufficient technological maturity and are widely practised, mitigation is the only way to reduce the rate of space debris growth.

At present, ISRO steadfastly pursues efforts to implement the internationally accepted guidelines and to continually improve compliance levels. Since the adoption of passivation of upper stages as a standard practice in 2002 and no upper stages have been reported to have undergone break-up . Safe lift-off clearance through LV-COLA is an integral part of all ISRO launches. Collision avoidance manoeuvrs are performed as and when needed to safeguard operational spacecraft, even those operating beyond Earth's orbital regime. Currently, ISRO's GEO satellites are designed with adequate propellant margins for re-orbiting to a higher orbit at the end of their useful life. They also undergo timely PMD, which guarantees 100% compliance with the PMD guideline. Similar fuel earmarking is planned for all future LEO missions to improve compliance. The restarting capability of PSLV upper stages has been a key contributor to a significant reduction in their residual orbital lifetime.

The current and future-projected space situation demands that every space-faring nation voluntarily undertake efforts for minimising space debris growth through cooperation and collaboration for sharing of data, experiences, and technical know-how. As a responsible space agency, ISRO shall

continue its pursuit of DFSM goals by ensuing compliance with SDMG, experience sharing, engagement with emergent space actors, and awareness-raising initiatives.

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References

18th & 19th Space Defense Squadron, United States: Space-Track. Accessed: 2024-12-11. https://www.space-track.org/auth/login

Adimurthy V, Ganeshan AS (2006) Space debris mitigation measures in India. Acta Astronaut 58(3):168–174

Agarwal A, Mukherjee B, Kandari A, Ramakrishna BN, Anilkumar AK (2022) Post-mission de-orbiting of Cartosat-2. Adv Space Res 70(5):1312–1324

Ananthasayanam MR, Anilkumar AK, Rao P (2006a) A new stochastic impressionistic low earth model of the space debris scenario. Acta Astronaut 59(7):547–559

Ananthasayanam MR, Anilkumar AK, Rao P (2006b) New approach for the evolution and expansion of space debris scenario. J Spacecr Rocket 43(6):1271–1282

Anil Kumar AK (2022) India's efforts in Space Debris Management. Technical Presentations made at the Scientific and Technical Subcommittee . https://www.unoosa.org/documents/pdf/copuos/stsc/2022/19_INDIA_Item8_Indias_efforts_in_Space_Debris_Management.pdf

Anil Kumar AK (2024a) The Dark Side of Space: addressing the space debris crisis. Technical Presentations made at the 31st Workshop on Space Technology for Socio-Economic Benefits:"Space Sustainability as a Game-Changer for Development" . https://www.unoosa.org/documents/pdf/psa/activities/2024/UN-IAF/Presentation/SatAM/Keynote_Dark_Side_of_Space_4Oct.pdf

Anil Kumar AK (2024b) A glimpse into long term sustainability efforts by India in 2023. United Nations Journal: Committee on the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee STSCJ2024-08E. Sixty-first session, Vienna, 29 January–9 February 2024

Anil Kumar AK, Ananthasayanam MR, Rao P (2005) A posterior semi-stochastic low earth debris on-orbit breakup simulation model. Acta Astronaut 57(9):733–746

Anilkumar AK (2005) New perspectives for analyzing the breakup, environment, evolution, collision risk and reentry of space debris objects. PhD thesis, Indian Institute of Science

Anilkumar AK, Reddy DS (2009) Statistical conjunction analysis and modeling of low-earth-orbit catalogued objects. J Spacecr Rocket 46(1):160–167

Anilkumar AK, Ananthasayanam MR, Rao P (2007) A constant gain kalman filter approach for the prediction of re-entry of risk objects. Acta Astronaut 61(10):831–839

Anz-Meador P, Opiela J, Liou J-C (2023) History of on-orbit satellite fragmentations. Technical report, NASA

Bandyopadhyay P, Sharma R, Adimurthy V (2004) Space debris proximity analysis in powered and orbital phases during satellite launch. Adv Space Res 34(5):1125–1129

Department of Space, Government of India: Indian Space Policy—2023. Accessed: 2024-12-11 (2023). https://www.isro.gov.in/media_isro/pdf/IndianSpacePolicy2023.pdf

Dutt P, Mutyalarao M, Bhanumathy P, Saritha Kumari TR, Negi D, Anil Kumar AK, Kumar A, Ashok V (2023) Assessment of in-house algorithms on re-entry time prediction of uncontrolled space objects. Adv Space Res 72(7):2535–2551

Gupta S, Anilkumar AK (2015) Integrated model for prediction of reentry time of risk objects. J Spacecr Rocket 52(1):295–299

IADC Steering Group and Working Group 4: IADC Space Debris Mitigation Guidelines. Issued by IADC Steering Group and Working Group 4 (2021)

IADC Working Group 4: Support to the IADC Space Debris Mitigation Guidelines. IADC-04-06 Rev. 5.8 (2021)

IADC: Inter-Agency Space Debris Coordination Committee. Accessed: 2024-12-11. https://www.iadc-home.org

Indian National Space Promotion and Authorization Centre: Norms, guidelines and procedures for implementation of indian space policy-2023 in respect of authorization of space activities (ngp). Technical report, Department of Space, Government of India (May 2024). Accessed: 2024-12-11. https://www.inspace.gov.in/sys_attachment.do?sys_id=5d532e37877102503b0f0d060cbb35cf

Indian Space Research Organisation: Atmospheric Re-entry of Cartosat-2. Accessed: 2024-12-11 (2024). https://www.isro.gov.in/press-meet-reentry-cartosat-2.html

Indian Space Research Organisation: Chandrayaan-2 Orbiter (CH_2O) performs an evasive manoeuvre to mitigate a critically close approach with LRO. Accessed: 2024-12-11 (2021). https://www.isro.gov.in/Orbiter.html

Indian Space Research Organisation: Dedication of ISRO System for Safe & Sustainable Operations Management (IS4OM) to the nation. Accessed: 2024-12-11 (2024a). https://www.isro.gov.in/IS4OM.html

Indian Space Research Organisation: India's Intent on Debris-Free Space Missions - Explained. Accessed: 2024-12-11 (2024b). https://www.isro.gov.in/Debris_Free_Space_Missions.html

Indian Space Research Organisation: Megha-Tropiques-1 (MT1) Controlled Re-entry Successful and impacted on the Pacific Ocean. Accessed: 2024-12-11 (2023). https://www.isro.gov.in/mt1-rentry-successful.html

Indian Space Research Organisation: Post Mission Disposal of GSAT-12. Accessed: 2024-12-11. https://www.isro.gov.in/PostMissionDisposal_ofGSAT_12.html

Indian Space Research Organisation: PSLV accomplishes zero orbital debris mission. Accessed: 2024-12-11 (2024). https://www.isro.gov.in/PSLVC58_POEM3_accomplish_zero_orbital_debris_mission.html

Klinkrad H (2006) Space debris: models and risk analysis. Springer, Heidelberg

Mukherjee B (2023) Post mission disposal of Megha-Tropiques-1 through controlled atmospheric re-entry. LPI Contrib 2852:6143

Mukherjee B, Anil Kumar AK (2023) Current practices and future requirements for safety of space flight for missions beyond earth's orbital regimes. LPI Contrib 2852:6112

Mukherjee B, Anilkumar AK (2021) Post mission disposal of Cartosat-2: Compliance with IADC guidelines. In: 8th European Conference on Space Debris, 135

Mukherjee B, Srikanth M, Parthiban P, Agarwal A, Srivastava R, Pillai JR, Gupta H, Mishra P, John LJ, Kandari A, Chacko T, Anil Kumar AK (2024) Post mission disposal of Megha-Tropiques-1 through controlled atmospheric re-entry to be published. J Space

Saf Eng 11(3):469–475. https://doi.org/10.1016/j.jsse.2024.05.006

Prasad M (2005) Technical and legal issues surrounding space debris—India's position in the UN. Space Policy 21(4):243–249

Sabarinath A, Anilkumar AK (2008) Modeling of sunspot numbers by a modified binary mixture of laplace distribution functions. Sol Phys 250(1):183–197

Sabarinath A, Anilkumar AK (2011) A stochastic prediction model for the sunspot cycles. Sol Phys 273:255–265

Sharma R, Bandyopadhyay P, Adimurthy V (2004) Consideration of lifetime limitation for spent stages in GTO. Adv Space Res 34(5):1227–1232

Sharma R, Anilkumar A, Xavier James Raj M, Sabarinath A (2009) On re-entry prediction of near earth objects with genetic algorithm using KS elements. In: Fifth European Conference on Space Debris, 672, 88

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